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厦门大学

硕士学位论文

Si 在漳江流域沿岸植物体内的累积及其对桐花树幼苗生理生态效应的研究

The Cumulation of Si in Plants Along Zhangjiang River and Its Ecophysiological Effect on *Aegiceras corniculatum* Seedlings

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摘要

针对漳江流域沿岸植物，研究了 48 种植物成熟叶片中 Si 元素含量，探讨 Si 含量在不同植物类群中和环境因子下的变化。进一步选择耐盐性红树植物桐花树(*Aegiceras corniculatum*)进行栽培，用不同的盐度处理，采用不加 Si 和加 Si 两组对比培养，通过存活率、生长状况和生理生态指标测定，研究了 Si 对桐花树耐盐性的影响。以期使 Si 这一重要的营养元素得到应有的重视，并为理解红树植物的耐盐机理和生态恢复提供一些理论依据。研究发现：

1. 漳江流域沿岸 48 种植物成熟叶片平均 Si 含量为 1.23%。不同植物叶片 Si 含量差异显著，含量最高的是木贼科的笔管草(*Hippochaete debile*)，达 5.88%，最低的是桃金娘科的桃金娘(*Rhodomyrtus tomentosa*)，仅 0.02%。48 种植物中有 17 种是 Si 积累者，它们叶片中平均 Si 含量为 2.53%；31 种非积累者叶片中的平均 Si 含量为 0.28%。从科级水平看，含 Si 量较高的主要有禾本科、木贼科、紫萁科、凤尾蕨科、鸭跖草科和桑科等科植物。

2. 从上游到下游，土壤 Si 含量随土壤颗粒变细和含水量升高而增加；并且在红树林区越往下游盐度越高。沿岸分布较广的马缨丹(*Lantana camara*)和鸭跖草(*Commelina communis*)叶片 Si 含量与对应土壤的有效 Si 含量呈正相关；而桐花树和秋茄(*Kandelia obovata*)2 种红树植物叶片 Si 含量与其生长的土壤中的盐度呈正相关。

3. 无论是否加 Si，桐花树幼苗的存活率和茎生长高度都在盐度 10‰时最高，在低盐(<10‰)和高盐(>15‰)的情况下，桐花树幼苗生长都受到影响。加 200mg·L^{-1}Si 的处理组，各盐度下幼苗的存活率和茎高度都明显高于对照组(CK)，而且不同浓度 NaCl 处理下存活率和茎高度的变化幅度较小，接近于盐度 10‰时的最佳状态。

4. 不加 Si 时，不同盐度处理的桐花树幼苗成熟叶片的叶绿素 a(Chla)、叶绿素 b(Chlb)和总叶绿素(Chl)含量变化基本一致，即随着盐度的增加，Chla、Chlb 和 Chl 含量都呈现先上升后下降的趋势，且含量都在盐度 10‰时达最大。而 Chla/b 值随盐度的增加表现出总体下降的趋势，虽然中间有小幅度的波动。加 Si 组相对只用盐处理组，Chla、Chlb 和 Chl 随不同盐度的变化趋势相似，即随着盐度的增加，Chla、Chlb 和 Chl 含量也都呈现先上升后下降的趋势，且含量都在盐度

10‰时达到最大，只是变化相对平缓，但是 Chla、Chlb 和 Chl 的含量比不加 Si 组普遍要高出很多。加 Si 组 Chla/b 值随盐度的增加表现出下降的趋势，在盐度 35‰时最低，但 Chla/b 值的变化相对于 Chla、Chlb 和 Chl 含量的变化比较平缓。

5. 无论加 Si 与否，叶片和根系中的丙二醛(MDA)大体上都呈现随着盐度增加先下降后上升的趋势。不加 Si 组在中等盐度下叶片中 MDA 含量与 CK 相比，降低显著；而加 Si 组叶片中 MDA 含量变化幅度小，且稳定在较低水平。不加 Si 时桐花树幼苗根系的 MDA 含量比叶片低，且变化幅度较大，在盐度 10‰时降低显著(P<0.05)，而当盐度很高时 MDA 含量相对 CK 明显上升。加 Si 后根系 MDA 含量更低，且各个盐梯度下的变化较小。

6. 幼苗叶片和根系中脯氨酸(Pro)的积累与盐度非线性正相关。不加 Si 和加 Si 条件下，桐花树幼苗叶片和根系中 Pro 含量都呈现随着盐度增加先下降后上升的趋势，均是在盐度 10‰时最低，在盐度 35‰时最高。加 Si 后叶片和根系 Pro 含量相对不加 Si 的叶片和根系各个盐度下均降低。不加 Si 和加 Si 两种情况下根系 Pro 含量都比叶片低，加 Si 组根系 Pro 含量更低，并且不加 Si 时 Pro 含量变化较大，而加 Si 时各种盐度下的变化平缓。

7. 不加 Si 和加 Si 两种情况下，叶片中超氧化物岐化酶(SOD)活性随盐度的增加都呈现出先上升，到盐度 10‰时达到峰值，然后下降的趋势，而且所有盐胁迫组叶片中 SOD 活性均高于 CK。不加 Si 时根系 SOD 活性在盐度 10‰时的最高值是 CK 的 1.20 倍，差异显著，而在盐度 35‰时 SOD 活性最低点时仅为 CK 的 95.92%；而加 Si 组在盐度 10‰时的最高点是 CK 的 1.17 倍，最低点就是 CK 本身。

8. 桐花树幼苗叶片中过氧化物酶(POD)活性变化趋势基本一致，在加 Si 和不加 Si 时都表现为随着盐度的升高先上升后下降的趋势，但其峰值有所不同，加 Si 组在盐度 10‰时 POD 活性最高，而不加 Si 组在盐度 15‰时最高，但在盐度 10‰时也较高。加 Si 组各个盐度下根系中 POD 活性普遍比不加 Si 要高，但优势并不是很明显。

9. 不同 Si 浓度处理下，桐花树幼苗的存活率和茎高度都是随着 Si 浓度的增加先增加，在浓度为 100mg·L^{-1} 时达到峰值后，反而随 Si 浓度的增加逐渐下降。很明显中等浓度的 Si(100mg·L^{-1} 左右)能促进桐花树幼苗的存活和茎生长，但高浓度的 Si 反而有抑制作用。

10. 桐花树幼苗成熟叶片中 Chla、Chlb 和 Chl 含量都随 Si 浓度增加现在上升后下降，在 100mg·L^{-1} 时最大，且不同 Si 浓度处理下含量均高于 CK。不同 Si 浓度处理下，幼苗叶片的 Chla/b 值随 Si 浓度的变化呈波动性上升趋势。

11. 随着 Si 浓度的增加，叶片和根系中 MDA 含量均呈先下降再上升的趋势。Si 浓度为 100mg·L^{-1} 时叶片 MDA 含量最低，此时 MDA 含量为 0.83μmol·g^{-1}FW，仅为 CK 的 65.67%；根系 MDA 含量最低值为 CK 的 75.61%，此时也 Si 浓度为 100mg·L^{-1}。不同 Si 浓度下根系的 MDA 含量与叶相比都较低，且不同浓度的 Si 处理对叶片中 MDA 含量影响较大，而根系的 MDA 含量保持相对的稳定，叶片膜脂过氧化程度更容易受 Si 影响。

12. 不同梯度 Si 处理时，桐花树幼苗叶片和根系中 Pro 含量都呈现随着 Si 浓度增加先上升后下降的趋势，且都是在 100mg·L^{-1} 时最低，根系中 Si 浓度为 200mg·L^{-1} 时 Pro 含量也很低，与 100mg·L^{-1} 时非常接近。相同 Si 浓度下桐花树幼苗根系 Pro 含量相对叶片较低，而且变化相对叶片平缓。

13. 随着 Si 浓度的增加，桐花树幼苗叶片和根系 SOD 活性变化趋势大致相同，都呈先下降后上升趋势。在叶中，SOD 活性在不同浓度 Si 处理下虽有变化，但变化的幅度不大，活性最低时为 CK 的 89.63%。根系中 SOD 活性远低于叶片，并且随不同浓度 Si 处理变化的幅度更小。

14. 桐花树幼苗叶片中 POD 活性随着 Si 浓度的增加先下降，在 Si 浓度为 100mg·L^{-1} 处达最小，随后上升，根系中 POD 活性的变化趋势与叶中基本一致。虽然各梯度 Si 处理下根系 POD 活性均比叶片低，但根系 POD 活性变化幅度相对叶片较大。

关键词：Si含量；富Si植物；桐花树；生理生态；漳江流域

Abstract

To explore the concentrations of Si in different plants and the ecophysiological effect of Si on plant, the Si concentration in mature leaves of 48 species of vascular plants along the Zhangjiang River was studied. Furthermore, the effect of Si on the salt-tolerant ability of mangrove plant was studied with *Aegiceras corniculatum* seedlings cultivated in Hoagland solution for 120 days. We expected that the importance of Si would be recognised, and provided theoretical gist for understanding the mechanism of salt-tolerance of *Aegiceras corniculatum* and the practice of revegetation of degraded forests in tideland area. The results showed that:

1. The average Si concentration in mature leaves of 48 plant species was 1.23%. Among these plants, the Si concentration in *Hippochaete debile* leave was the highest, up to 5.88%, and *Rhodomyrtus tomentosa* was the lowest, only 0.02%. The Si concentration varied significantly in different plant groups. The plants of Graminae, Equisetaceae, Osmundaceae, Pteridaceae, Commelinaceae and Moraceae were rich in Si. 17 of the 48 plant species were Si accumulators, in which, the average Si concentration was 2.53%, other 31 species were non-accumulators, in which, the average Si concentration was 0.28%.

2. We also noticed that from the upper reaches to the lower reaches along the Zhangjiang River, with the increase of water concentration and decrease of the grain size of soil, the Si concentration in soil increased accordingly, and the salinity was higher in the mangroves tideland soil in lower reaches than the upper reaches. The Si concentrations of the *Lantana camara* and *Commelina communis* had positive correlations with the effective Si concentration in the soil, which distributed wide along the river; while the Si concentrations of *Aegiceras corniculatum* and *Kandelia obovata* had positive relationships with the salinity in the soil.

3. The survival rate and the stem height *of Aegiceras corniculatum* seedlings were the highest under salinity 10‰. *Aegiceras corniculatum* seedlings can not grow well in the situations of higher or lower salinity. Both the survival rate and the stem height of the seedlings were promoted at each gradation in the group 200$mg \cdot L^{-1}$ Si was added, moreover the change of survival rate and the stem height were gentler, approaching the level under the medium salinity. Si may promote the survival rate of *Aegiceras corniculatum* seedlings and the stem height of seedlings under salt-stress

(low salinity and high salinity), made it restore close to the value of salinity 10‰.

4. With salinity increase, Chla, Chlb and total Chl concentrations all presented the tendency that rose first and then dropped, and the concentrations all reached the peak at 10‰ salinity. But the Chla/b value was toward a tendency of droping along with salinity increase, although had a small scope fluctuation. Compared with the group without Si, the change tendency of Chla, Chlb and total Chl concentrations in the with Si group was similar, and the only difference was the change relatively gentler. But the Chla, Chlb and Chl concentrations at all salinity were much higher than the group without Si. After added Si, the Chla/b value displayed a tendency of droping with salinity increase, the lowest was at salinity 35‰, but the change was quite gentler compared to the shift of Chla, Chlb and total Chl concentrations.

5. Regardless of with Si or without, the MDA concentration in the leaves of *Aegiceras corniculatum* seedlings was higher than in the roots. On the whole, in the situation with Si and without Si, the MDA concentrations in the leaves and roots presented a similar change tendency with salinity increase, that was dropped at first and then rose. In the treatment without Si, compared with CK, the MDA concentration in mature leaves of the medium salinity reduced obviously; but when added Si the change scope of MDA concentration was less in the leaves. Si kept the MDA concentration at a lower level in the leaves. The MDA concentration in the roots was lower than in the leaves, and it changed greatly in the group without Si. At salinity 10‰ the MDA concentration was the lowest, and the increasing was obvious relative to CK when salinity was higher. After adds Si, the MDA concentration was much lower in the roots, while the change was gentler under each salinity.

6. The Pro concentrations in the leaves and roots of the seedlings were not in line with salinity. In the situation with Si and without Si, the Pro concentration in the leaves and roots of the *Aegiceras corniculatum* seedlings all presented a tendency that rose first and then dropped with the salinity increase. Moreover in both situations, the Pro concentration in the leaves was higher than in the roots. When Si was absent, the Pro concentration in the leaves at medium salinity reduced obviously compared with CK. But in the situation of salinity 35‰, the Pro concentration was 1.21 times as high as CK. When Si was added, the Pro concentration in the leaves was in the trough at salinity 10‰, and the peak concentration was at salinity 35‰. When Si was added，Pro concentrations in the leaves and the roots reduced relatived to the group without

Si at each salinity. The Pro concentration in the roots was lower than in the leaves, and the change was remarkable compared to the group without Si. After added Si, the Pro concentration in the roots reduced, moreover the change was slighter at each salinity.

7. In the situation with Si and without Si, the SOD activity in the leaves presented rising with the salinity increase. It reached maximizations at salinity 10‰, then dropped. Moreover the SOD activities in the leaves of all salt-stressed groups were higher than the CK. Without Si, the SOD activity reached to the peak at salinity 10‰, and was 1.20 times as CK. At salinity 35‰ the SOD activity was only 95.92% of the CK. When Si was added, the peak value at salinity 10‰ was 1.17 times as CK, the trough was the CK itself.

8. In the situation with Si and without Si, the change tendency of POD activity in the leaves was consistent basically, which rose first and then dropped with the salinity increase. But the salinity at the peak was different slightly. The POD activity of the group without Si reached the peak at salinity 15‰, but the activity at salinity 10‰ was also high. The difference between them was not very clearly. In the situation with Si and without Si, the change tendency of POD activity in the roots was extremely similar to in the leaves, both reached the peak at salinity 10‰. The POD activity in the roots with Si was higher compared to without Si, but the superiority was not very obvious.

9. With Si concentration increase, the survival rate and the stem height of the *Aegiceras corniculatum* seedlings reached the peak at Si concentration of 100mg·L^{-1}. Before reaching the peak, the survival rate and the stem height rose fastly with Si concentration increase, but when the Si concentration increased ulteriorly, the survival rate and the stem height dropped gradually. It was very obvious that medium concentration of Si had a promoter action to the survival and the stem growth of *Aegiceras corniculatum* seedlings, but highly concentrated Si had a suppressant effect on seedlings.

10. The Chla, Chlb and Chl concentrations at each Si gradient were higher than the CK in the leaves of the *Aegiceras corniculatum* seedlings, and all the three reached the peak when the Si concentrations was 100mg·L^{-1}. But after that the Chla, Chlb and Chl concentrations all reduced with the Si concentration increase. When the Si concentration rose, the Chla/b value increased undulatorily in the leaves of the seedlings.

11. With Si concentration increase, the MDA concentration in the leaves dropped

first and then rose, and the lowest MDA concentration was 65.67% of the CK when the Si concentrations was 100mg·L^{-1}. The change scope of MDA concentration in the roots was narrow. The minimum MDA concentration was 75.61% of the CK when the Si concentrations was 100mg·L^{-1}. Under each Si gradient, the MDA concentration in the roots was lower than in the leaves. The effect of Si on the MDA concentration in the leaves was strong, but not so abvious in the roots.

12. The Pro concentrations in the leaves and roots of *Aegiceras corniculatum* seedlings all presented the tendency that first dropped and then rose with Si concentration increase. When the Si concentrations was 100mg·L^{-1}, the Pro concentrations in the leaves and roots were both lowest. But the Pro concentration in the roots was lower than in the leaves at each Si gradient, moreover the change was gentler relatively.

13. Treated with different concentration of Si, the change tendency of SOD activity in the leaves and roots of *Aegiceras corniculatum* seedlings was the same approximately, first dropped and then rose with Si concentration increase. Though the SOD activity in the leaves rose and dropped at different Si concentrations treatment, but the undulation scope was not wide, and the minimum activity was 89.63% of CK. In the roots, the change of SOD activity was even slighter.

14. With Si concentration increase, the POD activity in the leaves and roots of *Aegiceras corniculatum* seedlings dropped first, but it rose after reached the minimum when the Si concentrations was 100mg·L^{-1}. In the roots, the change tendency of POD activity was similar to the leaves nearly. Although under various Si concentration, the POD activity in the roots was lower than in the leaves, but the change scope of POD activity in roots was wider than in the leaves.

Keywords: Si concentration; Si accumulator; *Aegiceras corniculatum*; ecophysiological; Zhangjiang River

目录